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FIBRE CALORIMETERS: DENSE, FAST, RADIATION RESISTANT

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ABSTRACT

Dense electromagnetic calorimeters made of scintillating fibres embedded in grooved Pb sheets or similar configuration are described. The Omega Inner Calorimeter is entering its third year of successful operation. Some future prospects are discussed.

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1. INTRODUCTION AND SCOPE

The use of scintillating plastic fibres embedded in a Pb matrix has lead to the design and construction of electromagnetic calorimeters of record densities and good energy and spatial resolution. Table 1 gives a list of such calorimeters which are operating or under construction. A prototype which had the fibres running and read out in two orthogonal directions perpendicular to the particle beam was built and tested at the end of 1982 [1]. In the subsequent calorimeters, the fibres are nearly parallel to the particle direction and are read out on the back front of the converter, forming cell (tower) structures. The Omega Inner Calorimeter[2] was built and installed in summer 1984 and enters now its third year of successful operation. By the end of 1986, it will have been used by six experiments (WA69, WA70, WA71, WA76, WA81, WA83). The NA38 electromagnetic calorimeter[3] is being assembled and calibrated. It will be used later this year at a very high interaction rate (10^7 per burst of 2 sec) and radiation level (1 Mrad/week). A prototype of the DELPHI Small Angle Tagger[4,5] is under construction.

The outstanding characteristics of fibre calorimetry are so far:

- fast readout, by using blue scintillator readout via phototubes without the need for wavelength shifters (a gate width of 20 nsec will be used in the NA38 experiment to cope with its very high interaction rate).

- very high density, with an effective radiation length of L_{rad} = 1.1 cm in the Omega inner calorimeter, and L_{rad} = 0.85 cm in the NA38 calorimeter; and a very good hermeticity ("cracks" are due to mechanical imperfections, can in principle be avoided, and amount to a few percent of the subtended solid angle in the Omega case).

- a resistance to radiation typical of polystyrene, of which the fibres are made, superior to conventional PMMA (lucite) based scintillator and very much superior to Pb glass or BGO.

- a potentially good energy resolution [σ_E/E < 10% were measured around 1 GeV with structures of L_{rad} = 1.1 cm [1,2]].

The fibres are read by phototubes via light guides in the Omega (see Fig. 1) and NA38 calorimeters. Further technical improvements are under study by the DELPHI-Bergen group: use of the fibre ends as light guides, use of vacuum phototriodes or Si photodiodes[5]. The cost of fibre-lead converters has been found to be competitive with the prices quoted for lead glass blocks of similar granularity and covered area.

Table 1 does not include the multilayer cylindrical fibre hodoscope under construction for UA2 [6], which is not a calorimeter, although it does contain a layer of lead and will identify the initial shower development of electrons and photons.

2. FIBRE-Pb STRUCTURES, PRESENT TECHNIQUE AND PERFORMANCES

S.R. Borenstein and co-workers have experimented with scintillating plastic optical fibres since 1980 [7]. Mass produced polystyrene fibres were developed at Saclay[8] on our suggestion, and have been produced since 1984 by a private firm[9]. The refractive index of the polystyrene core is 1.59, the cladding has a thickness which is one percent of the fibre diameter, and an index of 1.46. Scintillation photons are transmitted along the fibres via total reflection on the core-cladding interface, if their angle with respect to the fibre axis is less than 23°, i.e. about 4% of all emitted light in either direction. We have tested fibres of diameter 0.3-2 mm, and built calorimeters with ϕ = 0.5 and 1 mm fibres. A XP2972 phototube sees five photoelectrons per mm of fibre traversed by a relativistic electron at 20 cm from the ϕ = 1 mm fibre end. For smaller diameters, the specific (per mm) scintillation light emission decreases. The light attenuation is roughly exponential beyond the first 20-30 cm, with attenuation lengths of 1.3-2 m.

Radiation resistance of the fibres has been measured by exposing them to ^{60}Co sources at doses of order 10-100 krad/h. The fibre degradation was exponential at these relatively high doses. The light emission was halved by a cumulative dose of 10 Mrad. The light transmission through 10 cm of fibre was halved by a 7 Mrad dose.

We had realized that structures which would completely surround each fibre by heavy metal would be capable of a better resolution than structures with alternating Pb sheets and fibre layers, for a given overall radiation length, i.e. volumic ratio of Pb to scintillator. Indeed, the average sampling thickness would be √2 times lower in a lattice type geometry. An elegant and promising technique developed at Saclay and based on a Pb alloy of low melting point[10)] did not produce the expected success, for reasons which were not fully understood. A private firm then suggested and subsequently produced a converter made of grooved Pb sheets (see insert in Fig. 1), into which the fibres were laid, and kept in place by gluing the next Pb sheet on top[11)]. In view of the modest sizes of the calorimeters built so far[2,3)] along these lines, the technique has been only partly automatized and requires a good degree of manual skill. Also, an early version of the fibre cladding was prone to damage from sudden temperature increases. The first Omega converter, made of ϕ = 0.5 mm fibre and roughly as much Pb as fibre in volume (L_{rad} = 1.1 cm) had to be built in record time and was far from perfect. It was later replaced by a new converter, based on ϕ = 1 mm fibre. The NA38 calorimeter was built of two volumes of grooved Pb for one volume of ϕ = 1 mm fibre (L_{rad} = 0.85 cm). It appears that calorimeters based on ϕ = 0.5 mm fibres, which are capable of better energy and spatial resolution, are hardly more difficult to build than ϕ = 1 mm fibre structures.

The complete structure of the Omega Inner Calorimeter is shown in Fig. 1, with its succession of three independent structures: the converter wall, the assembly of 32 x 32 mm^2 light guides (which do not necessarily have to match the block pattern of the converter), and the phototubes. This calorimeter had to fit tightly into the central gap of the larger outer calorimeter[12)]. It was therefore to be oriented at exactly 0°, and to detect the photons emitted between 0 and 10 mrad. The problem of photons which might impinge on a fibre and never see Pb was overcome by giving the converter blocks a wavy structure of a wavelength of ~ 3 radiation lengths and an amplitude somewhat larger than the fibre thickness. This was done by pressing the blocks between two appropriately shaped jaws while the glue was hardening.

The light attenuation length of the fibres embedded in the completed calorimeter was found to vary between 40 and 70 cm. Its effect on the energy resolution at high energy was reduced by sticking an adhesive mirror on the polished fibre ends opposite to those seen by the phototubes; and by using yellow filters to cutout the deep blue wavelengths which were more strongly attenuated.

The Bergen-DELPHI calorimeter is based on a Saclay technique which produces fibre layers bonded by double faced scotch tape, and allows planar Pb-fibre sandwich structures to be built with ease[13]. The ultimate resolution is less good (by a factor ~ $1/\sqrt{2}$) than for the lattice technique described above, but the fibres are better protected from mechanical damage and the actual test results are almost as good as with the best samples of the lattice technique (see next section).

3. TEST RESULTS

Figure 2 shows energy resolutions measured in electron beams for the four detectors discussed here. These are characterized by their configuration ("lattice" or "layers"), by the area seen by the beam (which accounts for lateral losses, especially in the case of the Omega and NA38 tests), and by a parameter t related to the sampling thickness in a slightly arbitrary way: t is the Pb plate thickness in the "layers" geometry, and the average Pb thickness between neighbouring fibres, in the "lattice" geometry. The resolution varies roughly as $\sqrt{t}$, at a given angle, it is slightly worse at small angles than at 90°, and the point at 0° is somewhat singular.

The published test results[1] of the 1982 prototype (Pb sheets of 0.5, respectively, 1 mm thickness alternating with layers of ϕ = 0.9 mm fibres running perpendicular to the beam) are, for electrons of 0.04-1 GeV,

$$\sigma_E = 7.8\%\cdot\sqrt{E} \quad \text{and } 9.8\%\ \sqrt{E}, \quad \text{and } \sigma_y \simeq 3\ \text{mm}/\sqrt{E}$$

for overall L_{rad} = 1.6 cm and 1.1 cm, respectively (E in GeV) (Fig. 2a).

Some particularly good converter blocks of the 1984 Omega calorimeter (ϕ = 0.5 mm fibres, L_{rad} = 1.05) were exposed to test beams of electrons between 0.5 and 50 GeV. The energy resolution (Fig. 2b) was found to be

$$\sigma_E = \sqrt{[(10\%/\sqrt{E})^2 + (2.2\%)^2]} \ .$$

The NA38 calorimeter is meant to measure the energy flux with moderate resolution; the number of impinging photons being comparable to the number of readout sectors, the reconstruction of π^0's is meaningless. The detector is calibrated in an electron beam, and has an energy resolution (for ϕ = 1 mm fibre and a volumic Pb:fibre ratio of 2:1) of $\sigma_E/E \simeq 20\%/\sqrt{E}$ (Fig. 2c).

A Bergen-DELPHI prototype (0.8 mm Pb foils, 1 mm fibre layers) was tested with electrons of 5-50 GeV and gave an energy resolution with negligible constant term[5] $\sigma_E/\sqrt{E} \simeq 12\%$ (Fig. 2d).

4. PERFORMANCE IN EXPERIMENTS

Actual exploitation results are available for the Omega Inner Calorimeter, mainly from experiment WA69 [14].

The uncalibrated detector was installed in July 1984 and produced a clean π^0 peak within a day, thanks to sophisticated software. These π^0's were used for an in situ calibration of each phototube and the corresponding converter cell. For the covered range of 25-100 GeV π^0 energies, spatial and mass resolutions rather independent of energy,

$$\sigma_y = 4 \text{ mm} \ , \quad \sigma_M/M_{\pi^0} = 9\%$$

were found, which were still adequate, but larger than expected from the test results. The blame is attributed to inhomogeneities in the light output of the converters. (The test results had been obtained with rather homogenous, selected blocks, and a small beam spot.)

The detector is now entering its third year of operation. Ageing has been estimated from the evolution of the calibration constants of converter cells over one year. The light output of the converters was found to diminish by 5-10% per year.

5. OUTLOOK

Further possibilities which should be explored include a superdense calorimeter of $L_{rad} = 0.5$ cm based on tungsten or densimet converter; and more audacious readout options using fibres emitting in the near UV region[14] which can be coupled to blue wavelength shifters of very fast response time (the conventional green wavelength shifter being rather slow).

But the new challenge is hadron calorimetry. R. Wigmans[15] has shown at this conference that full compensation of the losses in hadron signal due to nuclear excitation can be obtained, even with Pb, using the scintillator response to spallation neutrons. This requires a volumic Pb:scintillator ratio of 6:1. With conventional sandwich techniques using scintillator of several mm thickness, this leads to Pb sampling thicknesses of several radiation lengths, and hence a frustratingly bad resolution for electromagnetic showers. With the lattice geometry shown in the insert of Fig. 1, and $\phi = 0.5$ mm fibre, the equivalent sampling thickness is below 1 mm and a resolution for photons and electrons of $\sigma_E \simeq 10\% \cdot \sqrt{E}$ can be achieved. Direct readout from the back front of the converter offers clear advantages.

We are confident that the remaining technical problems with fibre calorimetry, which are limited and well circumscribed, can be solved within a project of adequate size. The triple bonus of compactness, short response time and good radiation resistance has been outlined above.

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Table 1

Main parameters of existing or planned fibre calorimeters. Resolution of Omega Inner Calorimeter is for reference blocks in test beams (E_T^o = transverse neutral energy, LG = light guides, θ part. fibres = angle of incidence of the particles with regard to the fibres, PM = photomultipliers, VPT = vacuum phototriodes; PD = photodiodes).

Detector, ref.	Prototype[1]	Omega Inner Calorimeter[2]	NA38 (O-U → μμ, E_T^o)[3]	DELPHI (Bergen) SAT (Small Angle Tagger)[4,5] Prototype	DELPHI (Bergen) SAT (Small Angle Tagger)[4,5] Detector
1st operation	End 1982	July 1984	1986	1986	1989
θ part. fibres	90°	0–10 mrad!	30–300 mrad	10–240 mrad	35–175 mrad
Fibre diameter	0.9 mm	0.5, then 1 mm	1 mm	1 mm	1 mm
Effective L_{rad}	1.1/1.6 cm	1.1 cm	0.85 cm	1.3 cm	1.3 cm
Converter volume	1.1 ℓ	50 ℓ	5 ℓ	5 ℓ	300 ℓ
Readout	Fibres, 36 PM	LG, 169 PM	LG, 30 PM	LG, PM	Fibres + LG VPT or PD
σ_E/E	9.8%/√E, 7.8%/√E	10%/√E+2.2% (Ref. block)	20%/√E	12%/√E	
Test range (GeV)	0.04–1	0.5–50	1–3.5	10–50	

Figure captions

Fig. 1 : The Omega Inner Calorimeter, located inside the central gap of the large Omega Photon Calorimeter and oriented at 0°; and the converter structure (schematic).

Fig. 2 : Measured energy resolutions vs. electron energy for a) the two configurations of the 1982 prototype (0.9 mm fibres, Ref. 1), b) test blocks of the 1984 Omega converter (0.5 mm fibres, Ref. 2), and vs. electron angle for c) big and small test blocks corresponding to the NA38 calorimeter (1 mm fibre, Ref. 3), and d) the Bergen-DELPHI test calorimeter (1 mm fibre, Ref. 5). The dotted lines show the parametrization (or averages) used in the text. The detector areas seen by the beam are indicated; lateral leakage occurs in b),c). The longitudinal leakage is negligible except for the NA38 calorimeter, of length 12 cm = 15 X_o. t refers to the sampling thickness (see text).

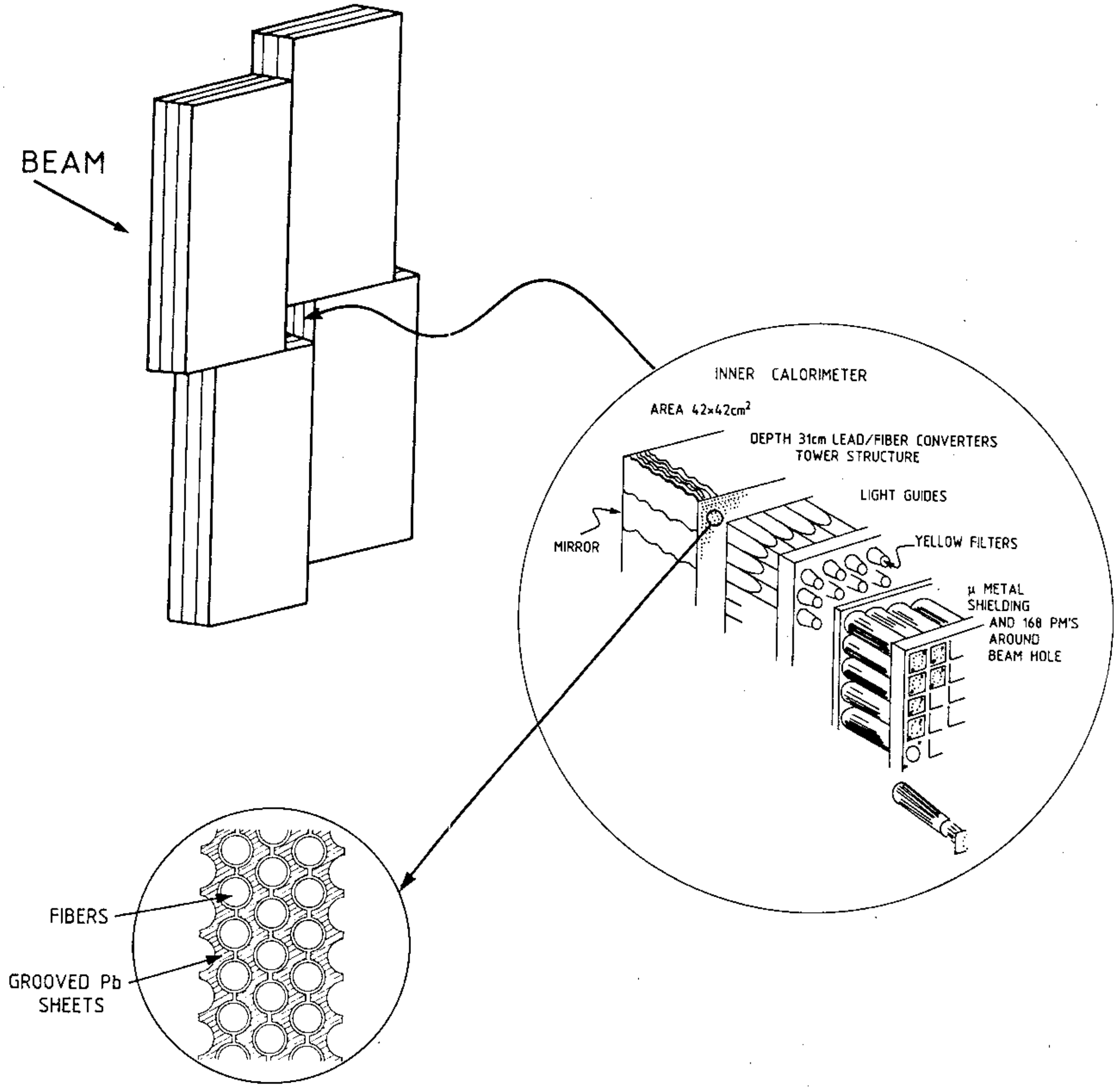
BEAM
INNER CALORIMETER
AREA 42×42cm²
DEPTH 31cm LEAD/FIBER CONVERTERS
TOWER STRUCTURE
LIGHT GUIDES
MIRROR
YELLOW FILTERS
μ METAL
SHIELDING
AND 168 PM'S
AROUND
BEAM HOLE
FIBERS
GROOVED Pb
SHEETS

Fig. 1

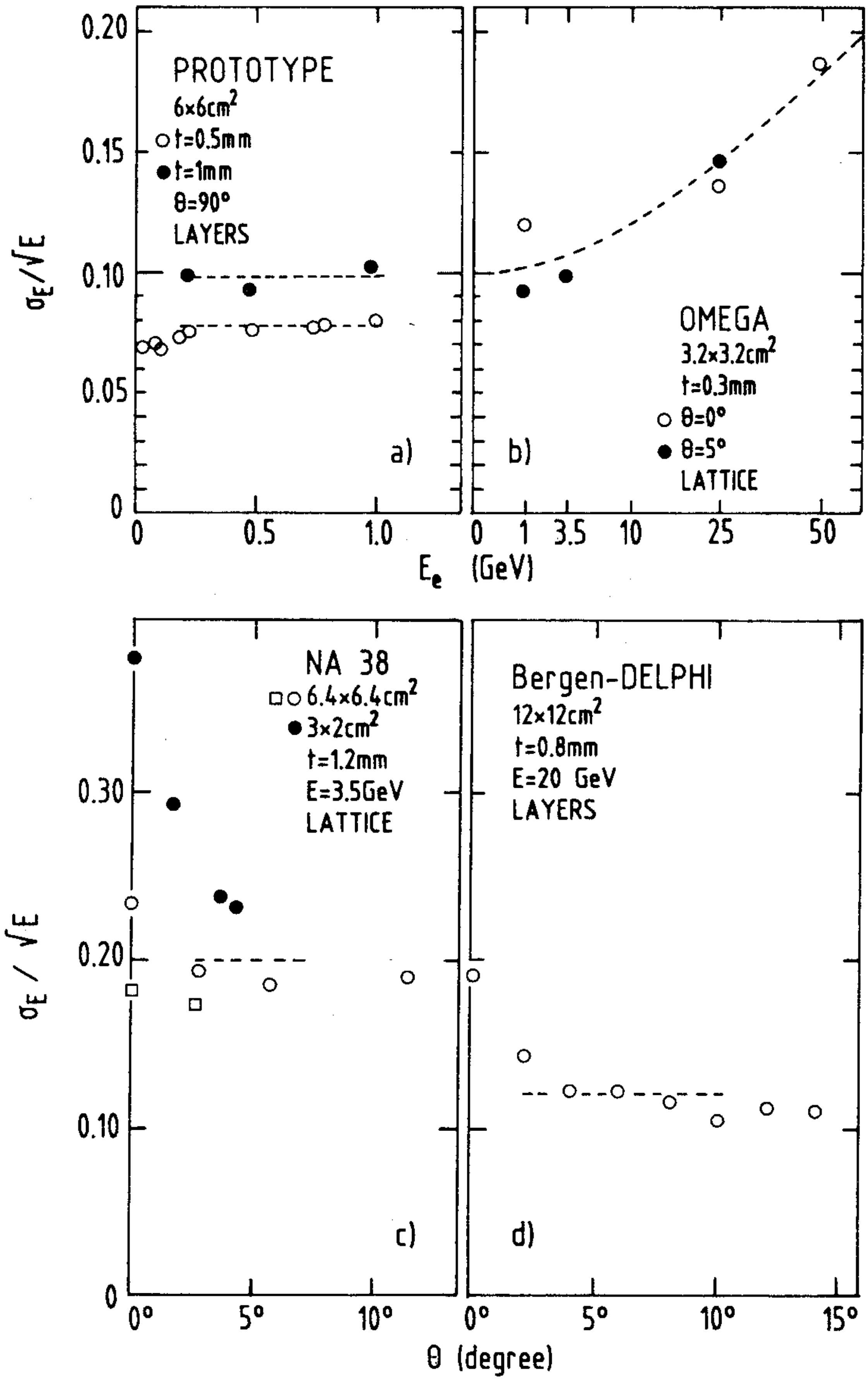
PROTOTYPE
6×6cm²
t=0.5mm
t=1mm
θ=90°
LAYERS
a)
OMEGA
3.2×3.2cm²
t=0.3mm
θ=0°
θ=5°
LATTICE
b)
σE/√E
Ee (GeV)
NA 38
6.4×6.4cm²
3×2cm²
t=1.2mm
E=3.5GeV
LATTICE
c)
Bergen-DELPHI
12×12cm²
t=0.8mm
E=20 GeV
LAYERS
d)
σE / √E
θ (degree)

Fig. 2